ON THE LOW-LEVEL STRUCTURE OF THE TYPHOON EYE

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ABSTRACT

Mean soundings are presented for the typhoon eye and storm circulation, based principally on dropsonde data taken by reconnaissance aircraft flying at the 700-millibar level. The vertical distribution of temperature and moisture shown by these soundings, and visual observations made in the eye, are used as a basis for a qualitative discussion of the pattern of vertical motion in the eye.

Introduction

The surface temperature-rise accompanying the arrival of the calm center of a tropical cyclone is occasionally quite marked. Outstanding examples of this phenomenon have been discussed by Deppermann (1937) and Tannehill (1943). In recent years, radiosonde flights made into the eye of hurricanes from coastal stations in the United States (cf. Simpson, 1947; Riehl, 1948) have shown the eye, at upper levels, to be warmer than the outside storm-circulation.

Recently, U. S. Air Force typhoon-reconnaissance aircraft have been making routine dropsonde observations into the eyes of typhoons. Some aspects of eye structure, based on the analysis of typhoon soundings taken in the western Pacific during 1951, will be presented below. Since most of the soundings were made from aircraft flying at the 700-mb level, the discussion is necessarily limited to the low-level portion of the eye.

Observational material

All available dropsonde and aircraft soundings made in the eyes and in the storm circulations of typhoons of the 1951 season have been used in this study. A total of 45 soundings was used; nine of these were made by the aircraft in ascent or descent. Thirty-five of the soundings were made in typhoon eyes, and ten in storm circulations from 100 to 400 km from the typhoon center. The soundings were taken in eight typhoons, located over a large expanse of the western Pacific between 10°N and 25°N, and 145°E and 115°E. There were soundings made in every month from July to December. The central pressure of the typhoons ranged from 900 to 905 mb.

There is little chance that any of the eye soundings left the eye before reaching the surface. The flight level was usually near 700 mb, and in all cases the eye diameter was in excess of 10 mi at the time of the dropsonde observation. These typhoons moved three miles, at the most, during the ten minutes or less taken by the dropsonde descent.

The instrumental difficulties involved in making both the dropsonde and aircraft observations are great. Errors are undoubtedly frequent. Consequently, for the most part, the data have been combined into mean soundings. The significance of the composite soundings is not nearly so dependent upon the accuracy of the measurements, provided the errors are random.

It has been possible to make qualitative checks on the reliability of the reported temperatures and the resulting lapse-rates. These include the relatively constant temperature of the ocean, the well-known moist-adiabatic lapse rate in the rain area of the storm which extends upward from the cloud bases, and the dry-adiabatic lapse rate in the sub-cloud layer. The only check for the moisture was the relation between the magnitude of the temperature-dew-point difference and the degree of stability usually observed in the presence of vertical motion, i.e., saturation with moist-adiabatic lapse rates and large dew-point spreads with great stability. On the basis of these checks it appears that (a) there were no systematic errors in the temperature measurement of the dropsonde, (b) there were small systematic errors in the temperature measurement made by the aircraft, and (c) there was some evidence that systematic errors may have been present in the dew-point measurement, particularly in those measured by the aircraft.

The aircraft temperatures measured in the storm circulation, i.e., outside the eye, appear to be too low. This was apparent on a large proportion of the soundings, since the uppermost observation in the dropsonde report--made at the flight level by the aircraft instruments--introduced an appreciable change in the lapse rate. These low temperatures reported by the aircraft in the storm circulation may have resulted from the large amounts of liquid water which are undoubtedly encountered. Liquid water, since it is incompressible, reduces the adiabatic heating which takes place about the thermomenters and their housing. No means are available to compensate for the effect of the water, and it appears that the application of a full adiabatic correction in such cases has resulted in temperatures which are too low, perhaps by as much as 1° to 2°C. Liquid water colder than the air and the effect of evaporation may also have contributed to lower dry-bulb readings. Errors made at the flight level have no effect on the temperatures measured by the dropsonde, since all checking and adjustment of the dropsonde instrument is made on the ground prior to the flight.

The aircraft temperature-measurements made in the eye appear to be consistent with the dropsonde temperature-measurements.

The aircraft dew-points in the eye appear to be too high in many cases. Dry air was rarely reported at the flight level. Saturation was often reported, even though the first dropsonde level below the aircraft showed a dew-point spread in excess of 5°C. Conversely, the aircraft dew-points in the storm circulation appear low in view of the observed lapse-rate, which approximated the moist adiabatic in most cases.

The dropsonde moisture-measurement is also open to some doubt. In particular, there were eye soundings which reported saturation at all levels when the lapse rate was more stable than the moist adiabatic.

Mean soundings for the eye and storm circulation

All available soundings have been used in computing mean soundings for the eye (fig. 1) and the storm (fig. 2). The individual soundings were plotted, pressure-height curves were drawn, and the temperature and dew point tabulated and averaged at 0.5-km intervals from the surface upward. It has been necessary to use height rather than pressure as the vertical coordinate, since the surface pressure varied over such a large range. For example, the 850-mb height varied from 1600 to 4600 ft in the eyes of the various storms. Moist adiabats can be entered on temperature-height diagrams only for particular values of pressure and temperature. The moist adiabats entered on figs. 1 and 2 have been computed with use of the mean surface pressures and temperatures of the eye and storm-circulation soundings as beginning points.

The lapse rate in the eye is appreciably more stable than the moist adiabatic above the 0.5-km level (fig. 1), while in the storm the lapse rate is slightly greater than the moist adiabatic (fig. 2). If the moist adiabat shown in fig. 2 could have been computed beginning at the mean height of the cloud bases, the storm circulation sounding would have shown less departure from moist-adiabatic conditions.

The mean sounding for the eye and the storm circulation and the mean hurricane-sounding computed by Schacht (1946) are compared in fig. 3. The greater stability and the warmer temperatures in the eye, in comparison with those of the storm circulation, are quite evident. The parallelism between the mean storm sounding and Schacht's mean sounding is quite marked. Apparently the warmer temperatures over the Pacific at all levels result from the fact that mean ocean-temperatures are warmer in the Pacific than in the Caribbean.

The tabulations of the mean storm-circulation and eye temperatures, and their range and mean deviation at 0.5-km intervals, are shown in table 1.

Table 1. Mean, range and mean deviation of temperature at 0.5-km height intervals in the typhoon eye and storm circulation.

Elevation	Temperature	Range	Mean deviation
	Eye		
Surface	25.7C	24-29C	1.0C
0.5 km	23.9	22-28	0.8
1.0	22.4	18-29	1.7
1.5	21.1	18-28	1.9
2.0	19.8	16-26	2.1
2.5	18.3	14-25	2.1
	Storm circulation		
Surface	25.7C	24-29C	1.0C
0.5 km	24.0	23-26	0.6
1.0	21.3	20-22	0.7
1.5	19.0	18-21	0.8
2.0	16.6	15-19	0.8
2.5	13.8	12-16	1.0
3.0	10.7	09-13	1.3

The smaller range and mean deviation above 1 km in the storm circulation, in comparison with the eye, indicate a greater homogeneity of the air outside the eye. It is also noteworthy that the surface-temperature range and mean deviation are the same in the storm circulation and in the eye.

Mean moisture

The dew-point curves of figs. 1 and 2 are very difficult to interpret. First, the dew points in the eye not only appear high in relation to the stable lapse-rate, but are even higher at most levels than those of the storm circulation. Secondly, the mean storm-circulation dew-points depart appreciably from saturation, despite a nearly moist-adiabatic lapse rate.

The individual soundings taken in the eye were for the most part either very dry or nearly saturated, with very few of the dew-point curves bearing any resemblance to the mean curve. These eye soundings may be accounted for by the fact that scattered to broken stratocumulus or cumulus, with tops to 6000-8000 ft, were usually reported in the eye. The difference between the moist and dry soundings may have been largely determined by whether the dropsonde descended in a cloud or in the clear spaces between clouds. On individual soundings, the variations of lapse rate and dew point were, in general, in the right sense, with the lowest dew-points shown in the most stable soundings and the highest dew-points when the lapse rate approached the moist adiabatic. The acceptance of the high dew-points in the eye, in the mean, requires an eye structure at low levels quite different from that ordinarily assumed. However, on the basis of cloudiness in the eye, discussed below, it appears that lateral mixing across the eye boundary is ordinarily active and that a well-defined eye boundary is seldom found. Even in the presence of lateral mixing, lowering of the dew point in the eye should be observed, particularly at upper levels. This difficulty can be resolved by rejecting the storm-circulation dew-points shown by fig. 2 and by assuming saturation in the storm, so that the dew points would be given closely by the temperature curve. The storm-circulation dew-points are rejected in favor of the eye dew-points because six of the ten soundings in the storm circulation were made by aircraft and because of their large departure from saturation.

Eye sounding of 15 August

There was only one eye dropsonde-observation available which extended much above the 700-mb level. The observation was made at 0200 GCT 15 August, in the eye of a typhoon located at approximately 20°N, 136°E. This sounding (fig. 4), taken about the time the storm reached its lowest reported pressure of 900 mb[1], shows a remarkably warm temperature of 15°C at the 500-mb level. The surface temperature, the low-level lapse rate and moisture, and the correlation between dew-point spread and lapse rate all appear quite reasonable. The eye was reported to have been filled with stratocumulus with tops to 6000 ft, and clear above. This is one of the few cases during 1951 in which middle and high clouds were reported to have been completely

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[1] There is no a priori reason for questioning the accuracy of this central pressure. Other dropsondes, taken August 14, 15 and 16, reported surface pressures of 922, 908 and 925 mb, respectively.

absent from the eye.

Starting with this warm temperature and low height at 500 mb, one might ask if the structure of the upper troposphere could be consistent with the following conditions: (a) that a nearly dry-adiabatic lapse rate exists for some distance above the 500-mb level, so that the 500-mb temperature could be accounted for by dry-adiabatic descent, and (b) that the cyclonic circulation of the typhoon disappears in the upper troposphere as, in general, all available evidence indicates. A calculation with use of upper-air data taken on 14 and 15 August at Guam, located about 1000 km southeast of the storm center, was carried out by assuming the 100-mb height over the storm center to be the same as that at Guam. Using the Guam 100-mb height of 54,500 ft and the measured 500-mb height of 16,900 ft in the eye, one finds the resulting lapse-rate to have been fairly close to the dry adiabatic, about 8°C per 1000 m; the 500-100-mb mean temperature was about -31°C; and the 100-mb temperature was in the vicinity of -75°C. The 500-mb temperature shown by fig. 4 would have required dry-adiabatic descent from about the 200-mb level. Since this computation has given reasonable values, no reason is seen for discrediting the 500-mb eye temperature of 16°C.

Visual aspects of the typhoon eye

The flight weather-reports made from the eye and the post-flight summaries usually give a verbal account of weather conditions encountered in the eye. These reports usually give the size and shape of the eye,[2] the amount and type of cloudiness, and occasionally additional information such as the state of the sea, turbulence, etc. These reports are not particularly amenable to statistical evaluation, since the same items are not always reported and since the inclination is always toward reporting the unusual phenomena. However, estimates of the size of the eye and descriptions of cloudiness were made with sufficient regularity that these data are summarized in the following paragraphs.

The cloud observations taken during 20 typhoon-days have been summarized. Two or more observations were made on some of the days. No observations made during these 20 days showed the eye clear of clouds at the lower levels. Cumulus or stratocumulus, with tops to 6000-8000 ft, were usually reported. The eye was reported completely clear above the flight level on only four out of the 20 days. An upper overcast was reported on 13 days; eight of the overcasts were of middle, and five were of high clouds. The middle-cloud overcasts were usually thin altostratus at heights of 10,000-14,000 ft. The eye boundary was rarely reported as a well-delineated wall of cloud. The ragged and ill-defined eye boundaries which were often reported are taken as evidence for mixing across the eye boundary.

The reported size of the eye diameter, shown by 46 individual reports, varied from 7 to 75 mi. The frequency distribution of the

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[2] Throughout this section, the eye is assumed to be that indicated by the clouds. It has been pointed out by Mr. Robert C. Gentry, U. S. Weather Bureau, that often the cloud eye is not coincident with the wind eye.

eye diameters is shown in the following tabulation:

Miles	Cases
Less than 15	5
15-19	4
20-24	5
25-29	5
30-34	7
35-39	5
40-44	9
45 and over	6

These data are somewhat biased, since there were more reports on some days and during some typhoons than others. There were five reports which stated that the eye was markedly non-circular. In all these cases, the major axis was at least 40 mi.

It is undoubtedly difficult to delineate the extent of the eye and to estimate the eye diameter accurately.[3] Furthermore, the eye is continually undergoing changes in shape and size. Reports made a few hours apart often showed variations of the eye diameter of 10-20 mi, particularly when the eye was large. No consistent pattern in the eye size as a function of the life cycle of the storm could be detected. For example, one typhoon, 12-17 August, maintained a fairly constant eye-diameter of 30-50 mi; another, 27-31 July, showed a progressive increase from 10 to 50 mi; and another, 27-29 October, showed a decrease from 30 to 10 mi. A scatter diagram of central pressure versus eye diameter (fig. 5) indicates that no good correlation exists between these parameters. However, some slight tendency is shown for the larger eye-diameters to be associated with the lowest central pressures. This is in agreement with the conclusions of Dunn (1951) in regard to hurricanes.

Conclusions

The data presented above are in agreement with the typhoon model advanced by Riehl (1951), the most complete one yet presented. However, the value of these reconnaissance data in testing this model has been greatly limited by the fact that, for the most part, they extend only to the 700-mb level. The moist-adiabatic lapse rate in the storm circulation, resulting from the adiabatic ascent of the air, and the stable lapse-rate in the eye, resulting from subsidence, both required by the model of Riehl, are substantiated (figs. 1 and 2). This model which deals with the larger-scale features, could not be expected to account for some of the smaller-scale features of the typhoon eye shown by this study.

The descending motion in the eye apparently does not extend to the surface, but often as low as 1 km. This conclusion is suggested by the height of the stable layer of individual soundings, and by the increase of the range and mean deviation of the temperature and potential temperature

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[3] It could not be determined from the reports to what extent aircraft radar was used in arriving at the eye diameter.

between 0.5 and 1.0 km (tables 1 and 2). Inspection of soundings showed that

Table 2. Mean, range and mean deviation of potential temperature at 0.5-km intervals in the typhoon eye.

Elevation	Potential temperature	Range	Mean deviation
Surface	302.7K	12C	2.6C
0.5 km	305.7	11	2.7
1.0	309.2	14	3.5
1.5	312.8	18	3.6
2.0	316.8	20	3.6
2.5	319.6	20	3.8

the base of the stable eye-layer was generally lower in the deeper storms. This correlation between the height of the base of the stable eye-layer and the central pressure of the storm is shown by fig. 6. In the preparation of this figure, heights of the stable layer have been averaged for 20-mb intervals of the central pressure, i.e., a mean height was determined for all storms with central pressures between 900 and 919 mb, 920 and 939 mb, etc.

No cases of marked surface temperature-rise, such as those presented by Deppermann and Tannehill, were noted. However, these surface temperature-rises, all of which occurred over land, presumably could have resulted from the extension of the descending motion to the surface. Conditions favorable for the breakdown of the shielding layer, which separates the descending air from the surface, would include insolational heating over land and down-slope motion due to orography. The importance of these factors in explaining the observed high temperatures has been stressed by Deppermann (1937).

Presumably, the vertical motion in the cloud areas of the eye is upward, but alternates with descending motion in the clear areas between clouds. This pattern of vertical mixing would imply large variations in the temperature and potential temperature, associated with changes in sign of the vertical motion. The range and mean deviation of the temperature and potential temperature in the 1.0- to 2.5-km region were found to be quite large (tables 1 and 2).

The soundings and the visual data suggest the following pattern of vertical motion for the eye: (a) subsidence in the upper regions, extending through a large portion of the troposphere and down to perhaps 500-700 mb, (b) a zone often extending nearly to the surface from this upper level in which vertical and lateral mixing takes place between the dry subsiding air and the moist air brought upward and inward from the storm, and (c) a shallow moist sub-cloud layer near the surface where the vertical mixing is suppressed. The fact that the surface air in the eye and the storm circulation is so homogeneous suggests that a net inflow of air probably takes place across the eye boundary near the surface, and that the net vertical motion in the sub-cloud layer is upward.

In this scheme, the outward mixing across the eye boundary, required from continuity considerations, would take place principally in the mixing layer.

It is difficult to estimate the magnitude of the lateral mixing required for the transfer of adequate moisture into the eye. If this mixing transfers only a negligible amount of angular momentum into the eye, such that it can be dissipated by weak pressure and frictional forces, the suggested circulation scheme appears to be phyically realistic. If, on the other hand, it can be shown that in accomplishing the moisture transfer into the eye an appreciable amount of angular momentum is added to the air inside the eye, this circulation scheme would appear doubtful. Since this question cannot be answered either way, it might be asked whether other mechanisms which avoid lateral mixing across the eye boundary could be advanced to account for the large amount of the moisture in the eye.

At least two alternative hypotheses which avoid lateral mixing could be proposed, but neither of these appear acceptable. First, it could be postulated that the cloudiness can be explained by introducing a shallow slope to the eye boundary, such that the surface eye is very small in comparison with the eye observed at the flight level. In fact, it might be postulated that the eye need not extend to the surface at all times. The clouds could be placed below the eye boundary in the storm circulation. However, there is no evidence that the eye size reported by ships and land stations is markedly less than that reported by the reconnaissance aircraft. In a few cases, the aircraft descended through the low clouds in the eye for soundings. These reports make no mention of narrowing of the eye or marked changes in the wind below the clouds. Secondly, a steady state condition for the eye could be postulated, in which the same air remains in the eye and the clouds are maintained in quasi-equilibrium in the layer below the stable region by the continual slow transport of water vapor upward from the ocean by turbulence and diffusion. This model would require that the air in the sub-cloud layer of the eye have a resultant velocity equal to that of the storm. The literature gives no evidence that the wind velocity in the eye shows any persistent direction. Furthermore, it is difficult to accept the eye in such a simple state, in view of the high wind-speeds and strong turbulence about the eye and the highly agitated state of the sea.

These hypotheses are rejected, and the model advansed for the eye, based principally upon thermo-dynamic considerations, can account for the eye moisture by lateral mixing. In such a model, the problem of the momentum transfer into the eye remains an open question. This scheme differs from those previously advanced principally in the degree of exchange between the eye and storm circulation, and the variable extent of the descending motion in the eye.

__Acknowledgment__

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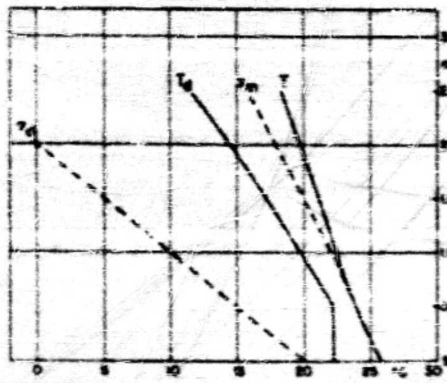

Fig. 1. Curves of mean temperature T and dew point T_d vs. height for eye of typhoon. γ_d and γ_m are dry- and moist-adiabatic lapse rates, respectively.

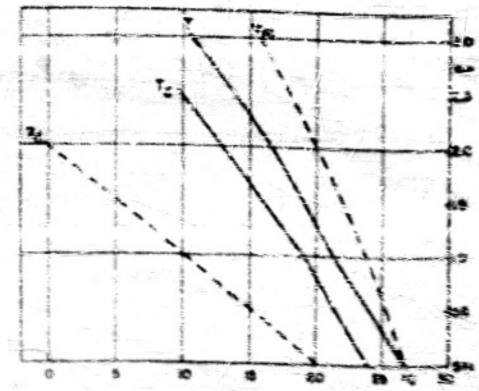

Fig. 2. Same as fig. 1, for storm circulation of typhoon.

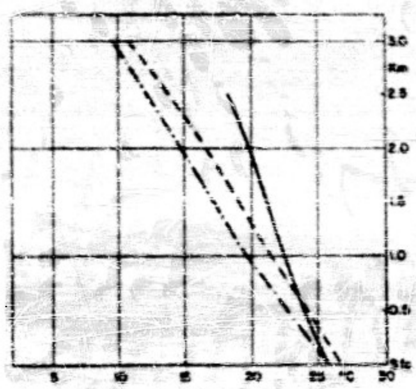

Fig. 3. Curves of mean temperature vs. height for eye (solid) and for storm circulation (dashed), and Schacht's mean hurricane temperature-curve (dash-dotted).

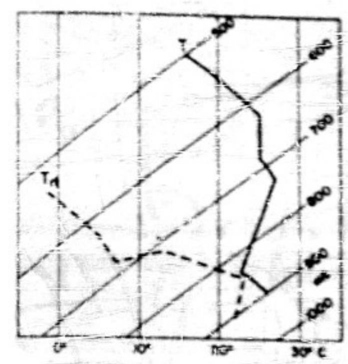

Fig. 4. Tephigram plot of dropsonde observation made at 0200 GCT 15 August 1951 into eye of typhoon near 20°N, 136°E.

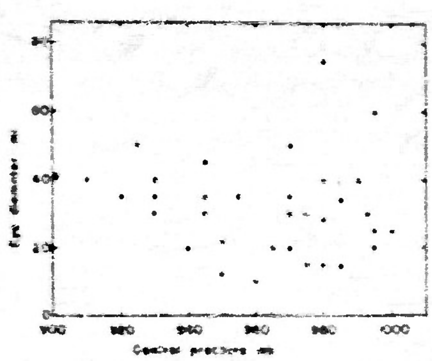

Fig. 5. Plot of individual reports of eye diameter vs. central pressure of typhoon.

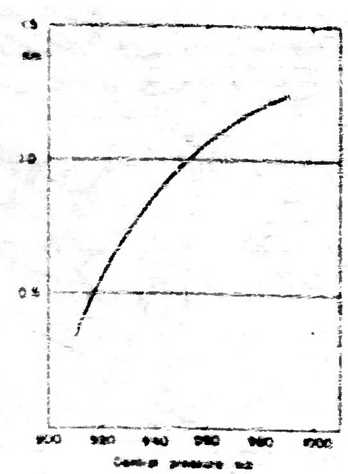

Fig. 6. Mean height of base of stable eye-layer vs. central pressure of typhoon.